FORECASTING PRECIPITATION WITH THE AID OF A HIGH-SPEED ELECTRONIC COMPUTER

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ABSTRACT

A high-speed electronic computer has been programmed to prepare cloud and precipitation forecasts for the Northern Hemisphere. The basic input data are derived from the Joint Numerical Weather Prediction Unit's two-level operational model of the atmosphere. The computer predicts cloudiness, rain, snow, and amounts of precipitation. Examples of computer forecasts are given and compared with observations.

1. INTRODUCTION

For the past five years the Joint Numerical Weather Prediction (JNWP) Unit at Suitland, Md., has been issuing upper-air forecasts based on the solution of the dynamic equations governing the large-scale flow of the atmosphere. Recently Carlstead [2] initiated experiments to see if useful forecasts of clouds and precipitation could be made based on the solution of the vorticity equation, the thermodynamic energy equation, and the continuity equations for air and moisture.

Since about 250 cloud and precipitation forecasts have now (June 1960) been made, it may be interesting to examine some of the results and to discuss some of the problems encountered. All the forecasts were made with the IBM 704 high-speed electronic computer.

2. THE BASIC EQUATIONS

The clouds and precipitation forecasting scheme makes use of the 500-mb. flow, the 1000–500-mb. thickness, and the vertical velocity derived from JNWP's operational 2-level forecasts. The equations governing the 2-level model of the atmosphere have been discussed by several authors, for example, 'Arnason and Carstensen [1]. For the sake of completeness, the equations are repeated here (though not in the explicit form used in calculations):

$$\frac{\partial\bar{\eta}}{\partial t}+\bar{\mathbf{V}}\cdot\nabla\bar{\eta}-K\frac{\partial\psi_5}{\partial t}=0 \qquad (1)$$

$$\frac{\partial\eta'}{\partial t}+\mathbf{V}'\cdot\nabla\bar{\eta}+\bar{\mathbf{V}}\cdot\nabla\eta'=\frac{\bar{\eta}\omega}{P} \qquad (2)$$

$$\sigma\nabla^2\omega-\frac{2f_0\omega}{P^2}=\frac{2f_0}{P}[\nabla^2(\bar{\mathbf{V}}\cdot\nabla\psi')-\bar{\mathbf{V}}\cdot\nabla\zeta'-\mathbf{V}'\cdot\nabla\bar{\eta}] \qquad (3)$$

where $\mathbf{V}$ is the vector wind velocity, ψ_5 is the stream function at 500 mb., $P=500$ mb., σ is a measure of the static stability, ω is the large-scale individual change of pressure with time, η is the absolute vorticity, ζ is the relative vorticity, and the bar and prime superscripts refer to the mean and half the difference, respectively, between 500-mb. and 1000-mb. values of the various quantities.

However, these equations do not take into account the moisture charge of the atmosphere and so a fourth equation (see Carlstead's [2] equation (2)) is added in the form

$$\frac{\partial T_s}{\partial t}=-\mathbf{V}\cdot\nabla T_s+\gamma W \qquad (4)$$

where T_s is the "spread", the difference between the temperature and the dewpoint; $\gamma=-8°$ C./km., the dry adiabatic rate of change of dewpoint depression; and W is the total vertical velocity taken to be $W=w+w_m$, where w is the large-scale vertical velocity in cm. sec.$^{-1}$ derived from the routine 2-level forecast and w_m is the vertical velocity due to the flow of air over mountains.

3. VERTICAL VELOCITY FORECASTS

The solution of equation (3) by the IBM 704 computer yields values of the vertical velocity associated with the large-scale features of the atmosphere. Small-scale vertical motions, such as those in thunderstorms, are excluded. The flow of air over mountains is another source of vertical motion in the atmosphere, and we have taken it into account by means of the relationship

*Most of the work on this paper was completed while the author was assigned to the Joint Numerical Weather Prediction Unit, U.S. Weather Bureau, Washington, D.C.

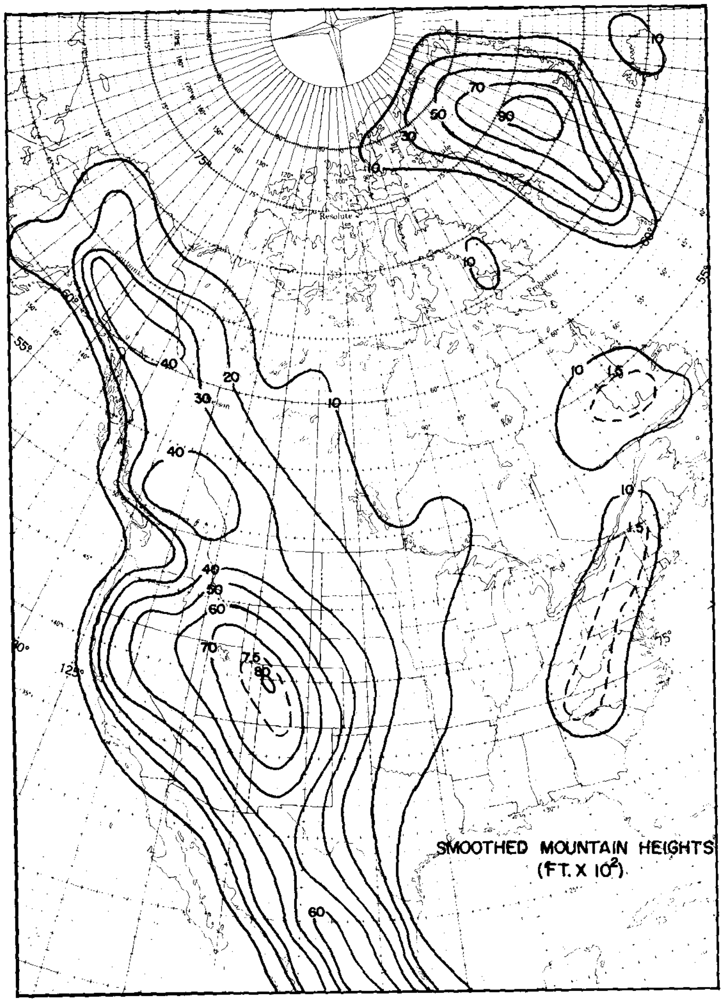


FIGURE 1.—Smoothed contour map of North America (in hundreds of feet).

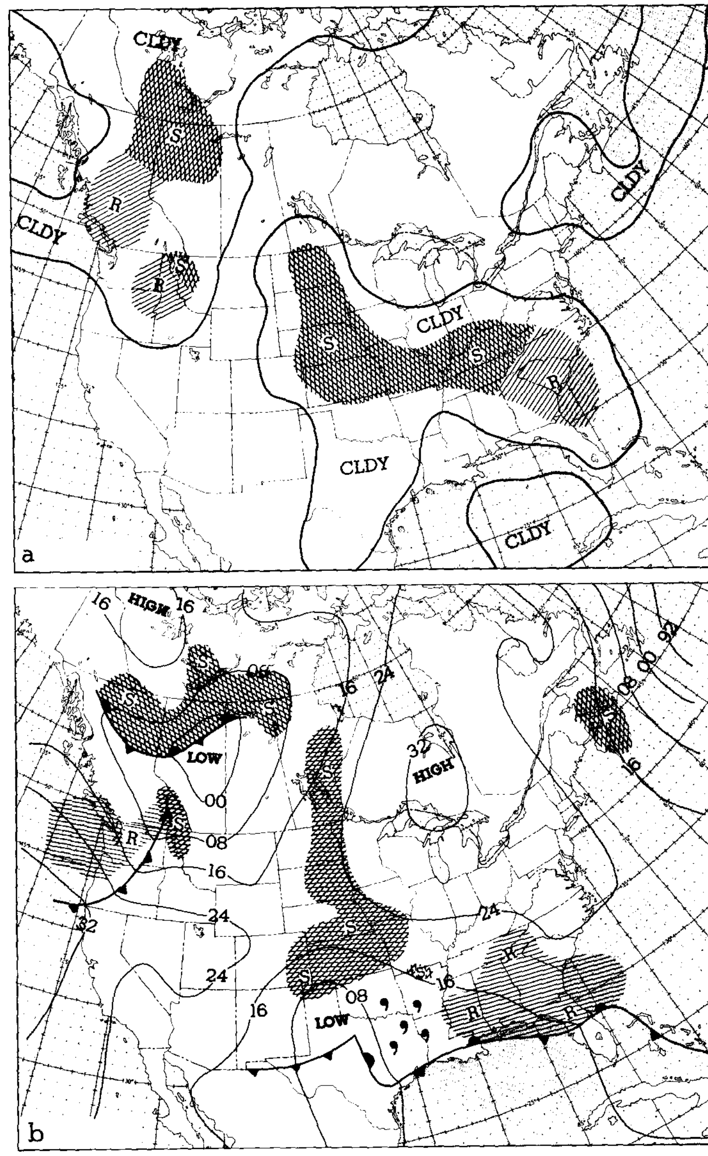


FIGURE 2.—1200 GMT, March 15, 1960. (a) 24-hour forecast of clouds and precipitation; (b) observed sea level pressure and precipitation patterns. R=rain, S=snow.

$$w_m = \mathbf{V}_g \cdot \nabla h \left(\frac{700}{p_g}\right)^{2.5} \tag{5}$$

where w_m is the mountain-produced vertical velocity in cm. sec.$^{-1}$, $\mathbf{V}_g$ is the wind (cm. sec.$^{-1}$) near the ground, p_g is the pressure (mb.) at ground level in the standard atmosphere, and ∇h is the slope of the ground.

The factor $(700/p_g)^{2.5}$ transforms the vertical velocity at ground level to that at 700 mb. The 700-mb. vertical velocity is assumed to be representative of that in the 1000–500-mb. layer. Estoque [5] suggested the use of the factor $(700/p_g)^{2.5}$, but its theoretical and empirical bases are slight.

The computation of w_m from the right side of equation (5) implies a knowledge of the topography of the Northern Hemisphere. We have made use of a simplified, or smoothed, contour map of the Northern Hemisphere, the North American section of which is shown in figure 1. If this figure is compared with an actual contour map of North America it will be seen that the actual contours bear only the crudest resemblance to those portrayed in figure 1. From this it follows that the numerical clouds and precipitation forecasts in mountain regions can hardly be expected to show the small-scale features characteristic of rough terrain.

4. CLOUDS AND PRECIPITATION FORECASTS

After the fields of wind and vertical motion are predicted, equation (4) is solved and the field of moisture is predicted for periods up to 36 hours in advance. In earlier experiments T_s was taken to be the temperature-dewpoint spread at 700 mb. But as that gave unsatisfactory results, it was decided to take the average of the 700-mb. and

850-mb. spreads to represent the moisture in the 1000-mb. to 500-mb. layer. The quantity ∇T_s, equation (4), is determined initially from an analysis of the moisture field. The 700-mb. wind field **V** is determined by interpolating between the 850-mb. and 500-mb. winds, both of which are available at hourly intervals from the routine 2-level forecasts.

The weather forecast is derived from an empirical relation, due to Lewis [7], connecting cloudiness and precipitation with vertical velocity and the temperature-dewpoint spread. This relationship, in the form of a table, is stored in the computer's memory.

From the computed values of the vertical velocity, the temperature-dewpoint spread, and Lewis' table, the computer specifies the amount of middle clouds and the occurrence of precipitation at each of the 1977 grid points on the Northern Hemisphere at 1-hour intervals. Figure 2 shows the 24-hour machine forecast of the weather for 1200 GMT, March 15, 1960, together with the observed weather map. The forecast was successful in some regions but failed in others. The snow area (S) from Kansas northward was well predicted, and so was the line separating rain (R) from snow in southeastern United States. But the observed drizzle area centered over eastern Texas was missed completely.

Because the moisture parameter used depends only on the 850- and 700-mb. spreads, the computer cannot predict the occurrence of drizzle and fog, which are associated with lower-level moisture, or cirrus clouds, which are associated with moisture near the 300-mb. to 200-mb. levels.

Another feature of figure 2 deserves mention: the distinction between rain and snow in the forecast. Studies by Wagner [12] and Lamb [6] have shown that the type of precipitation, rain or snow, is highly correlated with the thickness of the 1000-mb. to 500-mb. layer at the time precipitation is occurring. To their statistics data were added from several stationary ships in the Atlantic and Pacific Oceans and from land stations in Alaska and Canada. Then figure 3, showing isolines of equal probability of rain and snow, was prepared and stored in the computer's memory.

When precipitation is predicted, the computer, in effect, refers to figure 3 to determine the type of precipitation. If, at a given point, precipitation is predicted and the thickness is equal to or greater than the value shown on figure 3, the computer prints out R (for rain); if less, it prints out S (for snow).

5. QUANTITATIVE PRECIPITATION FORECASTING

For some purposes, flood forecasting for example, it is desirable to know the amount of precipitation to expect in the forecast period. To explore the applicability of computer techniques to the solution of the quantitative precipitation forecasting problem we proceeded along the lines suggested by Smagorinsky and Collins [10].

The rate R at which precipitation reaches the ground is

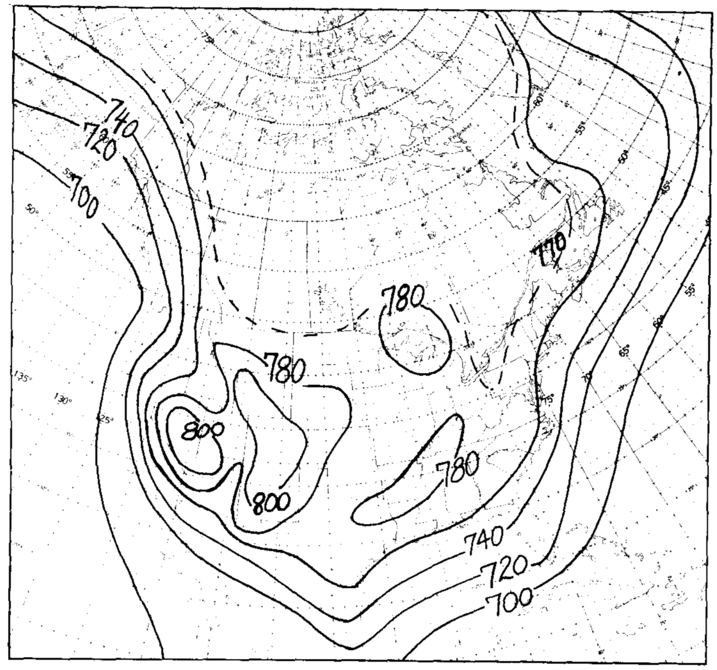


FIGURE 3.—Critical thickness (1000–500 mb.) which determines type of precipitation forecast. Thickness equal to or greater than value shown indicates rain forecast for that point; lesser thickness indicates snow forecast. (780=17,800 ft., etc.)

$$R=\int \frac{dr}{\rho_w g dt}\, dp \approx \int_{1000}^{500} \frac{dr}{\rho_w g dt}\, dp$$

where p is pressure, t is time, r is the humidity mixing ratio, and ρ_w is the density of liquid water. The integral should be taken through the entire depth of the atmosphere, but for many practical purposes the result is close enough if the moisture charge in the 1000–500-mb. layer only is considered. The amount of precipitation A accumulated over a time Δt is

$$A=\int_0^{\Delta t} R dt \approx \int_0^{\Delta t} \int_{1000}^{500} \frac{dr}{\rho_w g dt}\, dp dt$$

or

$$A \approx \int_0^{\Delta t} \int_{r_{1000}}^{r_{500}} \frac{\omega}{\rho_w g}\, dr dt \approx \frac{\omega}{\rho_w g} \Delta r \Delta t \tag{6}$$

By the time the computer reaches the stage where it is required to produce the quantitative precipitation forecast it already has stored in its memory the hourly values of the vertical velocity, the spread, and thickness at each of the 1977 grid points. The computer now examines each point to see if precipitation has been predicted. If so, it converts the thickness (or mean temperature) to the appropriate saturation mixing ratio, solves equation (6) for A, and stores the hourly amount of precipitation for each grid point. The process is repeated for each hour. Finally, the computer adds the amounts and prints out the total precipitation for 12, 24, and 36 hours.

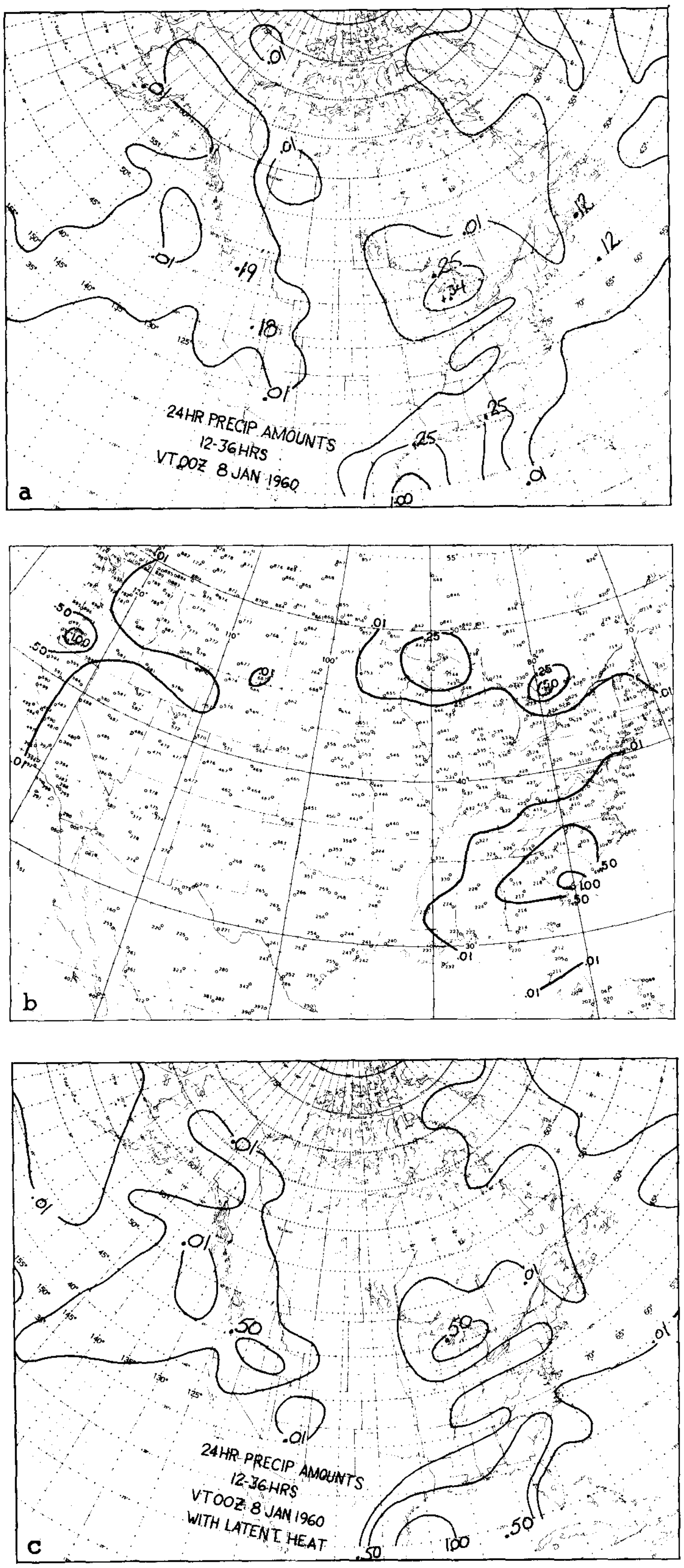


FIGURE 4.—0000 GMT, January 8, 1960. (a) 24-hour quantitative precipitation forecast (inches); (b) observed 24-hour precipitation; (c) 24-hour quantitative precipitation forecast with latent heat included in formula.

Figure 4a shows a 24-hour quantitative precipitation forecast for the period ending 0000 GMT, January 8, 1960. The forecast covers the period from 12 to 36 hours after the time of the data on which the forecast was based. Before comparing the observed precipitation (fig. 4b) with the forecasted, it may be better to discuss the problem of latent heat. Most investigators in the field of quantitative precipitation forecasting have found that current atmospheric models are incapable of predicting enough precipitation. Smagorinsky [9] has demonstrated that this results from the failure to take into account the release of the latent heat of vaporization. Following a suggestion by Smebye [11], the influence of latent heat was approximated.

The essence of Smebye's method is this. First, compute the vertical velocity by the solution of equation (3) and the precipitation amount—a first approximation. Then compute the amount of heat released by the precipitation. This leads to a correction to the vertical velocity, and in turn, results in an additional amount of precipitation. (The released heat is not allowed to change the flow pattern, which it most likely does.)

Figure 4c shows the predicted 24-hour precipitation amount, taking into account the release of latent heat, for 0000 GMT, January 8, 1960. Comparing figure 4c with 4b, one notices, first, that the precipitation forecast for eastern Texas was a complete failure. Over the remainder of the United States there is a fair correspondence between the forecasted and observed precipitation. Considerably more precipitation is predicted when latent heat is taken into account (fig. 4c) than when it is omitted (fig. 4a).

A rough comparison of forecasts made with and without the latent heat effect indicated that the maximum amount of precipitation predicted was about three times greater if the latent heat effect was included. This is in agreement with Manabe [8] who found that, while the ratio of vertical speed in a moist adiabatic atmosphere to that in a dry adiabatic atmosphere is variable, in middle latitudes it usually has a value ranging from 2 to 5.

On further comparison of figure 4b with 4c one finds that the predicted half-inch line in western Oregon is observed in eastern Oregon and Idaho. This is a characteristic error of the model. The use of smoothed mountains leads to predictions of precipitation farther inland than actually observed.

To summarize, this is how the computer makes a quantitative precipitation forecast:

1. Determines, for each of the 1977 grid points, if precipitation is predicted. If no, the process stops. If yes,
2. Notes the 1000–500-mb. thickness value and the total vertical velocity.
3. Reads a table that gives the amount of precipitation per hour as a function of thickness and vertical velocity.

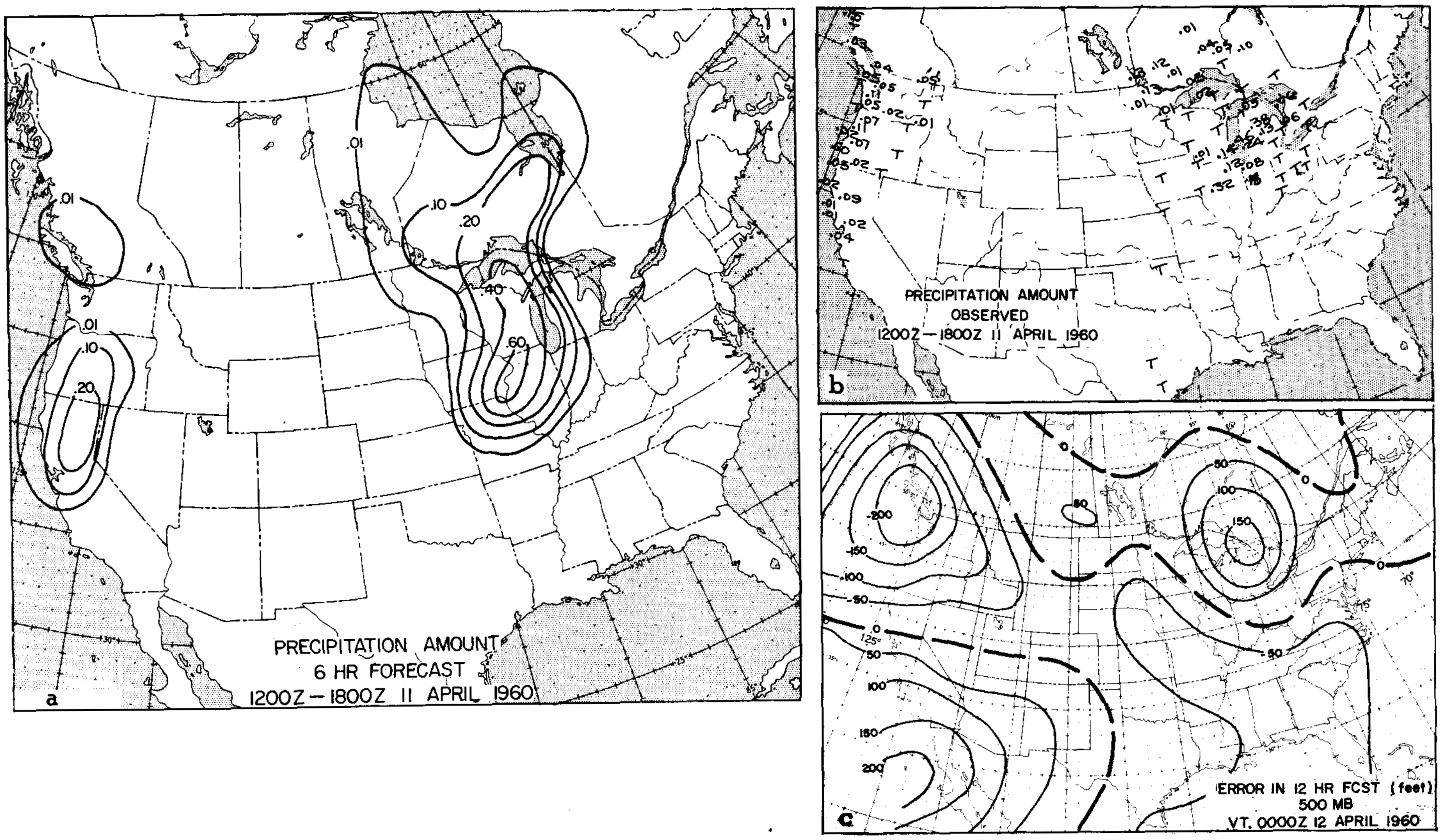


Figure 5.—Precipitation 1200–1800 GMT, April 11, 1960. (a) Forecasted; (b) observed. (c) Error in 12-hour 500-mb. forecast (ft.) for 0000 GMT, April 12, 1960 (forecasted minus observed).

4. Stores the hourly precipitation amount for each point.
5. Corrects the vertical velocity by an amount depending on the quantity of heat released by the precipitation.
6. Reads the table again, using the corrected vertical velocity.
7. Stores the new hourly precipitation amount in place of the old.
8. Repeats the process for each hour.
9. Adds the precipitation amounts.
10. Prints the total 12-, 24-, and 36-hour precipitation amounts for each grid point.

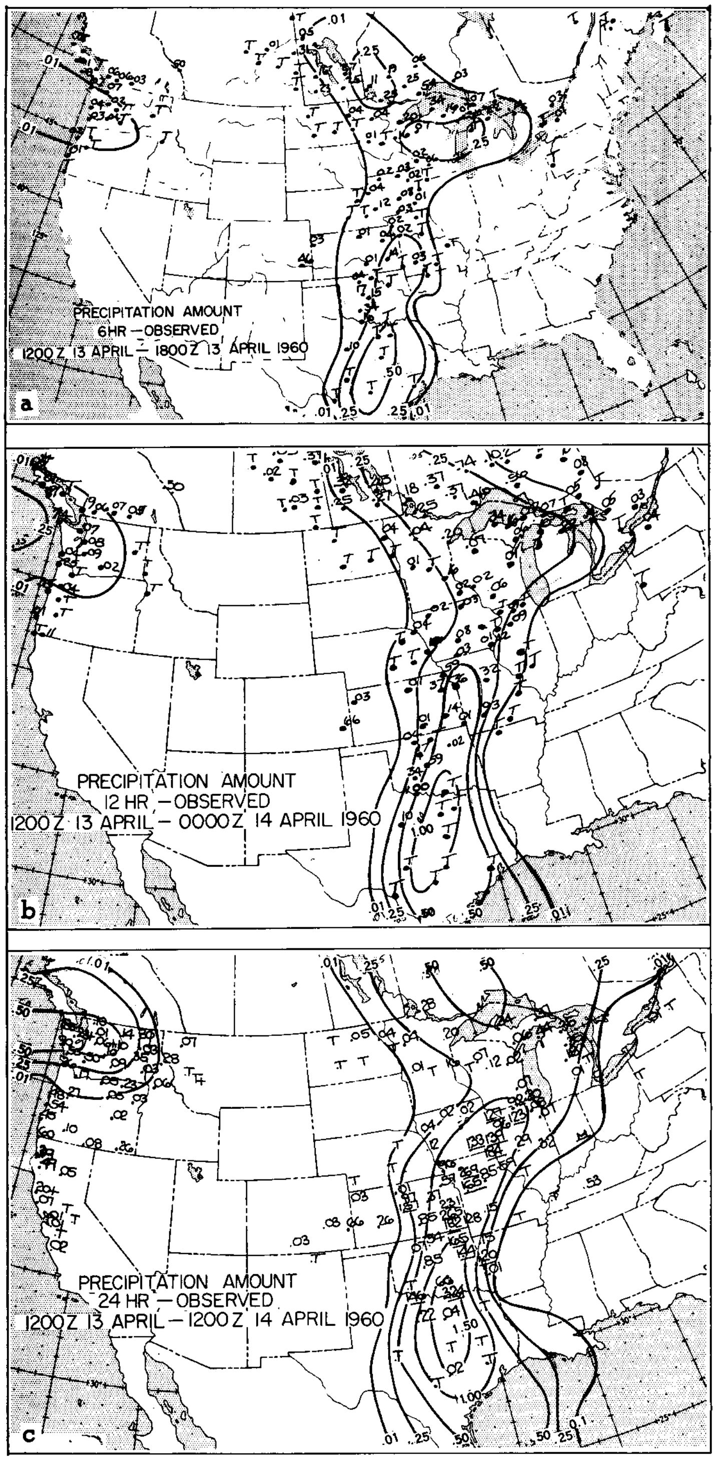
6. TESTING THE MODEL

Suppose the computer had made a perfect forecast of the 500-mb. flow pattern and the thickness field, would the model give a perfect precipitation forecast? To put it another way: Does the model contain the proper physical ingredients to enable it to predict precipitation correctly? A start was made to write a program that would enable the computer to get a precipitation forecast from a perfect forecast of the fields of flow and thickness (i.e., from observed data), but manpower shortages prevented completion of the job. And so a basic question remains unanswered.

Without much effort, however, one is able to get useful information about the quality of the atmospheric model. Several years of verification had shown that computer-made 24-hour 500-mb. forecasts were very good and that 12-hour forecasts were excellent. Therefore, the assumption was made that 6-hour forecasts were "nearly perfect." Six-hour observed precipitation amounts were then compared with the computed predictions.

Figure 5 shows the observed and predicted 6-hour precipitation amounts for the period 1200 to 1800 GMT, April 11, 1960. The largest amount of precipitation was forecasted in northern Illinois, but observed in Michigan. More precipitation was forecasted than observed in the western United States. The overall forecast may be considered a good one. One reason for the differences between the observed and forecasted precipitation may be found from an examination of figure 5c.

Figure 5c gives the error in the 12-hour 500-mb. forecast for the period 1200 GMT April 11 to 0000 GMT, April 12. The first half of this period corresponds to the 6-hour precipitation period under discussion. It would have been better to have a 6-hour 500-mb. error chart but that is not available. The 12-hour 500-mb. error chart, however, is routinely printed out by the computer. In the area over Michigan the 500-mb. forecast was 150 feet too high. Synoptic experience suggests that a lower 500-mb. height



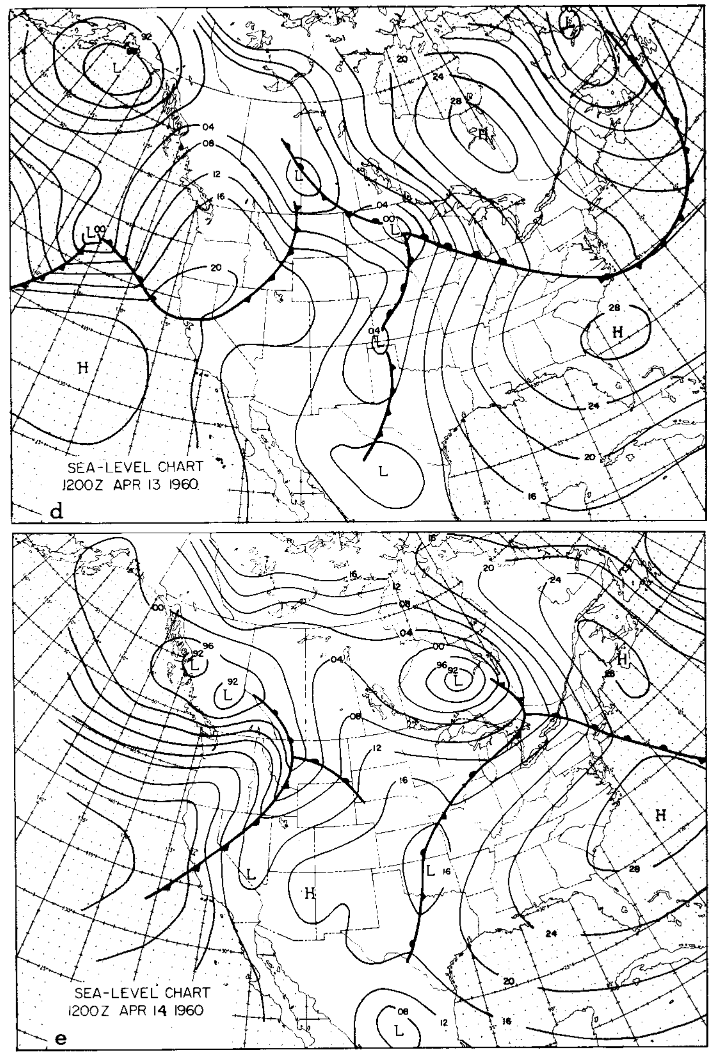


FIGURE 6.—Predicted and observed precipitation. (a) 1200 to 1800 GMT, April 13, 1960; (b) 1200 GMT, April 13 to 0000 GMT, April 14, 1960; (c) 1200 GMT, April 13 to 1200 GMT, April 14, 1960; (d) sea level chart, 1200 GMT, April 13, 1960; (e) sea level chart, 1200 GMT, April 14, 1960.

forecast would have improved the precipitation forecast there. The error chart also shows that our assumption of a nearly perfect 6-hour 500-mb. forecast was, most likely, not altogether correct. In the west, errors in the precipitation forecast are just as likely due to lack of knowledge of the initial conditions over the ocean as to a faulty model.

Since the computer calculates and stores precipitation amounts for each hour, the values may be printed out for various periods and the march of computed precipitation across the country compared with that of the observed precipitation. Figure 6 shows the predicted and observed amounts of precipitation as well as the movements of the precipitation areas for the 24 hours from 1200 GMT, April 13 to 1200 GMT, April 14, 1960. The forecast has caught the main features of the observed precipitation patterns.

From an examination of 6-hour precipitation forecasts, the impression emerges that the precipitation model is basically sound. It is unable to cope with the details of the mountain effect. The lack of information over the oceans and the Gulf of Mexico is sometimes disastrous to the forecast. A principal difficulty may be the inadequacy of the essentially barotropic model in predicting cyclogenesis with which large amounts of precipitation are associated. Further, the model cannot hope to forecast such small-scale phenomena as individual convective showers and thunderstorms.

7. SMALLER-SCALE OROGRAPHIC PRECIPITATION

In western United States, as is well known, the mountains have a strong effect on the distribution of precipitation. Since grid points are about 240 miles apart in the JNWP computational grid, and since the slope of the mountains is determined from the heights of points 480 miles apart, it is clear that the important features of the distribution of precipitation in western United States cannot be predicted.

Aside from the fact that current numerical weather prediction models do not permit the dynamics that are applicable to small-scale orographic motions, the main reason these methods use grid intervals of not less than 200 to 300 miles is that if shorter space intervals are used shorter time intervals must also be used in the integration of the governing differential equations. Short integration time steps mean a longer time to produce a forecast. Machine time is expensive. But as the computation of vertical velocity due to the flow of air over mountains, equation (5), does not involve the solution of a differential equation, Lt. Col. H. A. Bedient of JNWP Unit suggested experimenting with a much smaller grid interval.

Some computations have been made using a grid interval of 40 miles in the States of Washington and Oregon. These States were selected for test because of the rugged character of the country and the large space variation of mean annual precipitation amounts. Consider a saturated moist adiabatic atmosphere with a 700-mb. temperature of $-6°$ C. and a west wind of 20 knots ($\mathbf{V}_g$). The precipitation pattern due to the flow of air over the mountains, if these conditions hold for 24 hours, is shown in figure 7. An interesting feature of figure 7 is that it demonstrates that the flow of air over the mountains is sufficient to give heavy rains without the introduction of the latent heat effect. The amounts and pattern of precipitation bear a strong similarity to those frequently observed on the synoptic weather map., i.e., the precipitation is concentrated along the coastal mountains and, farther inland, along the Cascade Range.

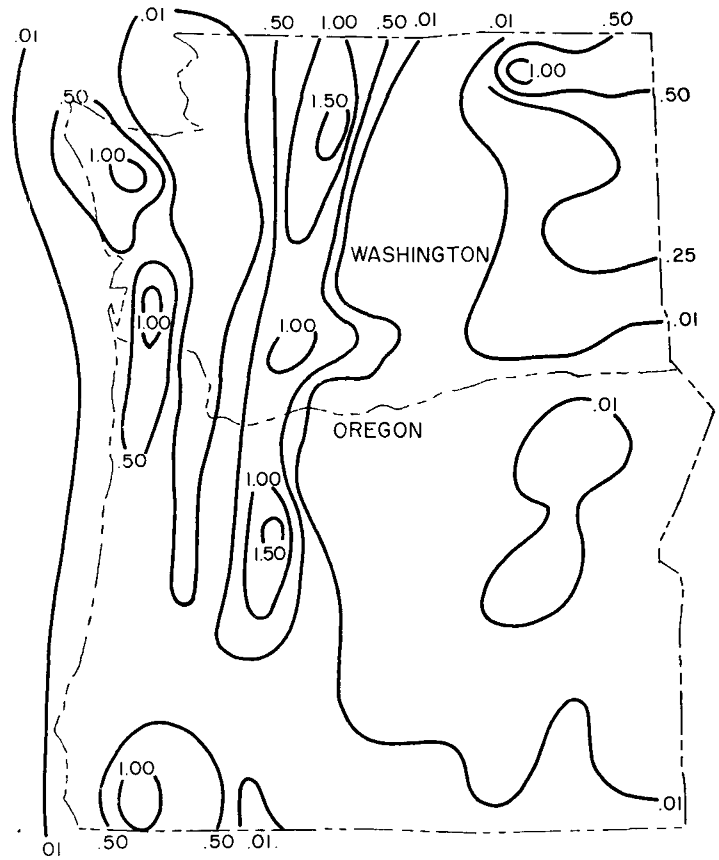


FIGURE 7.—Precipitation amount (inches per day) from a saturated atmosphere with a 700-mb. temperature of $-6°$ C. and a 20-knot west wind at the ground.

8. PROBLEMS AND SUGGESTIONS

Friction.—All the precipitation forecasts have been made without taking into account the vertical velocity due to surface frictional flow into Lows and out from Highs. However, the friction program has been written and checked out and will be incorporated into the main program shortly. The effect of friction on the 500-mb. flow has recently been taken into account by Cressman [3].

Showers.—Much of the summertime rain in the United States falls in showers. It seems best to tackle this problem with a probability forecast. Stanley Doore of JNWP Unit has written a program to enable the computer to print out the probability of the occurrence of showers. His work is based on the studies of Curtis and Panofsky [4].

Rain and snow.—The use of the 1000–500-mb. thickness as the only parameter to distinguish between rain and snow needs further examination. The use of another parameter, such as the 850-mb. temperature, may improve the forecast.

Some thought has been given to have the computer predict snow depth—a weather element of critical importance in the winter. It is easy for the computer to keep track of the predicted amount of precipitation that falls as snow. Precipitation amount can be transformed to snow depth by the computer by use of the standard 10 to 1 ratio (snow depth to water equivalent). But difficulties arise if both rain and snow are predicted during the forecast period.

Multi-level models.—The present precipitation forecasts depend on the simple atmospheric models now in use. As more sophisticated atmospheric models come into use, improved forecasts of the fields of flow, temperature, and moisture may be expected. Multi-level models of the atmosphere will be used in the powerful new IBM 7090 computer which was installed in JNWP Unit in mid-1960.

9. VERIFICATION

From what little verification has been made of the computer forecasts of precipitation, it seems that so far as "heavy precipitation"—1 inch or more in 24 hours—is concerned, the subjective forecaster is doing better than the computer. The reason for this is not clear. It may be that the latent heat effect is taken into account too crudely, or that the moisture field near the ground has to be considered. But perhaps the trouble is more fundamental. Examination of all the heavy rain cases for April 1960 in the contiguous United States revealed that most of the heavy rains were on so small a scale that they could not possibly have been predicted with the coarse grid used. If further study reveals that this is generally true, a smaller grid interval will have to be used to successfully predict heavy precipitation.

However, if the verification is made on the basis of "precipitation" or "no precipitation", it turns out that the computer-made precipitation forecasts are of about the same quality as subjective forecasts.

ACKNOWLEDGMENTS

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